Optical Focusing via Epsilon-Near-Zero Plasmonic Metalens

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Abstract-An ENZ metamaterial is engineered using a parallel plate plasmonic waveguide working near the cut-off of the transverse electric TE_1 mode. The ENZ region can be displaced to different wavelengths when the electrical width of the sandwiched dielectric is changed. Several converging lenses are designed at λ_0 = 474.9 nm with a focal length of 10.75λ_0: a smooth concave, zoned and graded refractive index (GRIN) lens. It is demonstrated that the best performance in terms of the focal length and volume reduction is achieved with the GRIN design, achieving values of 10.23λ_0 and ~52%, respectively.

Within the framework of metamaterials [1], media with low permittivity, so-called epsilon-near-zero (ENZ), have become a prominent subfield of research due to their unusual characteristics such tunneling, supercoupling and energy squeezing [2]. These features have been demonstrated at microwaves [3] and also at optical wavelengths using waveguides close to the cut-off of the TE_{01} mode and also by metal-dielectric-metal multilayers, respectively [4], giving rise to different applications such as sensors[5] and lenses[6], [7].

In this work we use a plasmonic parallel plate waveguide in order to engineer an effective ENZ medium by working near the cut-off wavelength of the TE_1 mode under vertical polarization (electric field parallel to the waveguide) [8]. It is shown that the ENZ region can be tuned at different wavelengths within the optical spectrum when the width of the sandwiched dielectric of the plasmonic waveguide is changed. Several converging lenses are designed at λ_0 = 474.9 nm and evaluated numerically: a smooth profiled plano-concave lens, a zoned lens and a graded refractive index (GRIN) lens.

To begin with, the schematic representation of the waveguide is shown in Fig. 1(a) as an inset. Silica (SiO_2) is used as dielectric in between two silver plates (modeled as a Drude model). A vertically polarized planewave (E_y) is used to excite the structure in order to work with the transversal electric TE_1 mode. The propagation constant (β) of this structure is calculated by using the dispersion equation of a plasmonic waveguide (see [8]). This parameter has a clear dependence on the width of the dielectric slab (h_x) as can be corroborated in Fig. 1(a) where the complex value of β is shown for the case of a plasmonic waveguide with h_x = 95 nm and h_x = 110 nm. It can be observed that the cut-off wavelength moves to longer wavelengths when h_x increases, as expected. Around this inflection point β is close to zero, which is one of the properties of an ENZ medium. Therefore, it is possible to work within this region and emulate an ENZ metamaterial.

Based on this structure, we design several lenses working at λ_0 = 474 nm with different profiles as shown in Fig. 1(b-d), in order to focus an incoming planewave at a focal length (FL) of 10.75λ_0. The numerical results of the normalized power distribution along the *z*-axis are shown in Fig. 1(e) for all the designs. The best performance is achieved for the GRIN design with a FL = 10.23λ_0, while it is at FL = 14.4λ_0 and FL = 11.3λ_0 for the lenses in Fig.1(b) and (c), respectively. Furthermore, a reduction of volume of ~52% is achieved with the

GRIN lens, which is attractive from a practical point of view.

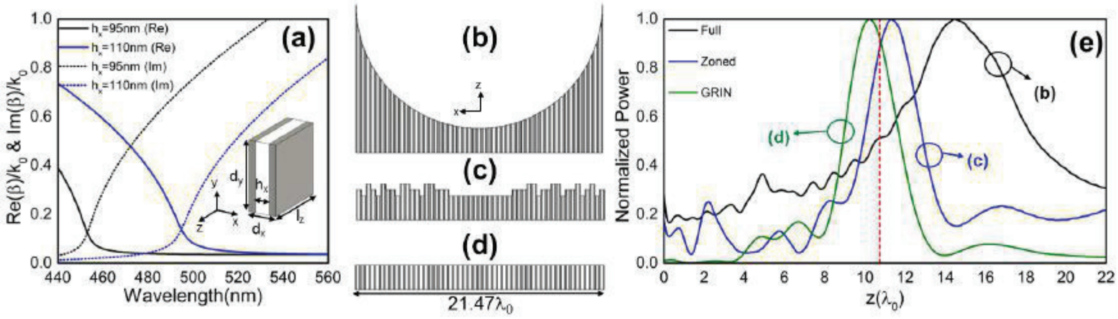

Figure 1. (a) Real (solid lines) and imaginary (dotted lines) parts of the propagation constant (β) normalized to the wavenumber in free-space(k_0) for two plasmonic waveguides with h_x=95nm (black) and h_x=110nm (blue). Schematic representation of the metalenses with profiles: (b) plano-concave, (c) zoned and (d) GRIN. (e)Normalized power distribution along the *z*-axis for the three converging lenses under study along with the design FL (red dashed line).

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